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# Should Environmental Standards be Tighter if Technological Change is Endogenous?

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## Abstract

This paper develops a growth model in which pollution, environmental quality and accumulation of clean technologies are endogenous. It is examined how the optimal environmental policy changes if the contribution of endogenous technological progress to total productivity growth increases. Short-run pollution reduction should be larger. However, optimal emission reduction rates in the long run may be lower because endogenous technology imposes a larger burden of investment and implies a larger persistence of the adverse effects of emission reductions on productivity. Only if growth is endogenous and long-run productivity falls as a result of environmental policy, also the steady state optimal level of environmental quality is higher because of endogenous technological change. Hence, this paper argues that endogenous technological change urges for early action and disfavors a wait-and-see strategy.

Keywords: optimal environmental standard, endogenous technological progress, induced technological change, endogenous growth.

JEL codes: Q28, O41.

ERN fields: Environmental Economics, Macroeconomics.

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## 1. Introduction

Evaluations of alternative policies towards sustainable development heavily depend on assumptions about future technological development. E.g. Nordhaus (1994) finds that the optimal economic policy in response to global climate change is most sensitive to technological parameters.<sup>1</sup> Goulder and Schneider (1995) refer to the results of other models developed to assess policies to reduce greenhouse gas emissions. The Stanford Energy Modeling Forum finds in a comparison of 14 models that the results are quite sensitive to the assumption on the rate of energy efficiency improvements.

However, technical change is traditionally considered as a non-economic variable in policy evaluation models.<sup>2</sup> It is exogenous in most policy evaluations as well as economic theory. This obviously hampers thinking about sustainable development. Porter and Van der Linde (1995) argue that environmental policy triggers technological change that may result in very inexpensive ways to reduce pollution. Goulder and Schneider (1996) argue that the neglect of induced technological change is an omission that leads to underestimation of the net benefits of pollution abatement. They provide a calibration of the US economy and point out that induced technological progress may have large effects on the costs of greenhouse gas reduction. Other economists point to the dangers to rely on new technology as an "automatic" response to changing incentives.

Are policies towards sustainable development "easier" if technological development responds to economic incentives, that is if technology is induced or endogenous? Should we pursue tighter environmental policies and faster pollution reduction schemes than is recommended in studies based on exogenous technology? These questions provide the background for the theoretical investigations in this paper. Modern growth theory is used as a tool to find some basic insights. The most obvious route to take is to compare models in which technological change is exogenous, with models from the new growth literature in which technology is endogenously accumulated.

The new growth theory was initiated by Romer (1986) and Lucas (1988), who developed models in which the long-run rate of economic growth and technological change is endogenously determined. Higher propensities to save, lower allocative distortions or larger technological opportunities have permanent effects on economic growth. The crucial assumption that gives this results is the absence of diminishing returns to reproducible factors

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<sup>1</sup> Optimal (sustainable) per capita consumption levels are more sensitive to technological parameters than to any other type of parameters in the empirically calibrated DICE model. Optimal sustainable output levels and CO<sub>2</sub> emission reduction rates are most sensitive to population growth and discount rate, but these variables are still more sensitive to technological parameters than to climate change parameters or damage parameters. See Nordhaus (1994) chapter 6.

<sup>2</sup> An exception is e.g. Carraro, Galeotti and Gallo (1996) who include endogenous technological change.



of production.

Environmental issues are explored within endogenous growth models by e.g. Bovenberg and De Mooij (1997), Bovenberg and Smulders (1995, 1996), Hofkes (1996), John and Pecchenino (1994), Elbasha and Roe (1996) (see Smulders 1995a for a survey). These environmental endogenous growth models mainly served to answer the following main three questions: (i) Under what conditions are economic growth and environmental preservation compatible, i.e. is sustainable development feasible? (ii) Under what conditions is sustainable growth optimal? (iii) How does environmental policy affect economic growth? The models are small analytical general equilibrium models that allow a formalization of sustainable development and the channels of interaction between environmental policy and economic growth. Before insights from these new models are transposed to larger scale models for policy purposes, it is important to know how the assumption of endogenous technological change will affect the conclusions about environmental policy based on models with exogenous technological change.

We should be careful, however, when we compare the different types of growth models. Models with endogenous technological change are not necessarily endogenous growth models, because despite opportunities for the endogenous accumulation of technological know-how, the overall returns to reproducible factors of production may be diminishing. Recent empirical contributions to growth theory seem to disfavor the basic characteristic of endogenous growth theory that changes in investment rates have permanent growth effects. Mankiw, Romer and Weil (1992) argue that not only physical capital is an essential reproducible factor of production, but also human capital. They find that marginal returns to reproducible factors of production are less diminishing when human capital is included, but they still diminish so that the neoclassical property is maintained. Jones (1995) shows that changes in investment rates have transitory effects only and proposes a model of endogenous technological change in which the long-run growth rate is still exogenous due to diminishing returns with respect to physical capital and knowledge accumulation.

This discussion suggests that it is appropriate to separate endogenous technological change from endogenous growth. Therefore, this paper develops an exogenous growth model with endogenous technological change. Due to the presence of diminishing returns with respect to reproducible production factors, the long-run rate of output growth is equal to the exogenously given rate of "basic" technical progress. However, the parameter that represents the contribution of economic research efforts to overall technology levels (or the degree of endogeneity of technological progress) affects the cost of environmental policy. Endogenous growth arises as a limit case of this model, namely the case in which technology is completely endogenous and the returns to capital are constant. The long-run growth rate then depends on preference and technology parameters, among which the parameter that captures the desire for a clean environment and the technology parameters that link the productivity of the economy



to the quality of the natural environment.

The main findings of this paper can be summarized as follows. The presence of endogenous technological change is a reason to reduce long-run pollution levels *less*. The reason is that, the more important endogenous technological change is and the less the economy relies on exogenous productivity improvements, the larger is the part of national income that has to be spent on investment to maintain a given rate of growth. This implies a lower consumption ratio. As a result, material consumption is scarcer so that it is more costly to redirect investment from investment in material standards of living to investment in the environment. In the short run, however, pollution should be reduced *more* if technology is endogenous rather than exogenous. Policy evaluation based on exogenous technological change biases policy recommendations against early action. The intuition behind this result is that with endogenous technology, energy taxes and pollution restrictions not only reduce production and physical capital investment, but also technological progress. Hence, investment in the assets on which the economy relies becomes more difficult and rates of return are more persistently lower than when exogenous technological change easily makes up for productivity losses. Lower rates of return to economic investment imply lower opportunity costs of environmental investment so that investment in a clean environment should be increased.

Section 2 presents the model. Section 3 develops a graphical solution procedure for the steady state. Section 4 and 5 discuss environmental policy in the steady state of the exogenous and endogenous growth model respectively. Section 6 and 7 consider the short-run environmental policy implications of the two models. Section 8 summarizes how the introduction of endogenous technological change affects optimal environmental policy and assesses the merits of endogenous growth models.

## 2. The model

This section presents a simple model to explore the interaction between economic growth and environmental policy. It is a generalization of the models explored in Smulders (1995b) and Bovenberg and Smulders (1995, 1996).<sup>3</sup> Our economy produces a single final good. Utility depends on consumption of this good and on the quality of the environment. The economy can accumulate productive assets, which include technology capital, by devoting some fraction of output to investment. In order to improve environmental quality, i.e. to invest in natural capital, reductions in pollution are necessary at the cost of declining production. Finally, the

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<sup>3</sup> Here we distinguish between "exogenous" and "endogenous" components of the knowledge stock, while in the cited papers all knowledge is derived from investment. The cited papers also deal with the decentralized economy where firms maximize profits and consumers maximize utility, whereas this paper only considers the first best economy.



economy experiences exogenous improvements in technology in addition to investment-driven technological change. The importance in production of the latter relative to the former will characterize the degree of endogeneity of technological change.

Ecological processes are modeled as growth and depletion of a renewable resource, according to the following equation:<sup>4</sup>

$$N = E(N) - P, \quad E_{NN} < 0, \quad (1)$$

where  $N$  denotes environmental quality or the stock of natural capital. Nature has a capacity to renew itself as captured by the term  $E(N)$ . Both extraction of natural resources (where the environment acts as a source) and the disposal of wastes (where it acts as a sink) are represented by  $P$ , since both activities diminish the stock of available natural resources. As long as the economy uses less environmental services than are provided ecological processes, i.e.  $P < E(N)$ , environmental quality improves over time. Nature is able to absorb a maximal amount of pollution without deteriorating,  $P = E(N)$ , so that  $E(N)$  represents the absorption capacity of the environment. Sustainable development can be defined by  $N = 0$  and requires that in the long run pollution  $P$  is constant and does not exceed the maximum absorption capacity.

Economic activity is represented by a production function<sup>5</sup>  $Y(\cdot)$  and the goods market equation:

$$Y = Y(K, h_1, h_2, N, P) = C + \dot{K} + q\dot{h}_1. \quad (2)$$

Production generates consumption goods ( $C$ ), new capital goods ( $K$ ), and new knowledge ( $h_1$ ). Inputs in the production process are capital ( $K$ ) and natural resource inputs ( $P$ , e.g. energy, but also space, clean air, etc), technical knowledge ( $h_1$  and  $h_2$ ) and nonrival services from the environment (captured by  $N$ ). Environmental quality  $N$  enters the production function because a higher environmental quality renders the economy more productive. This might happen because the health of workers is improved which boosts labour productivity, the cost of harvest or extraction is lower, soil productivity is higher, or because a richer biodiversity provides a larger pool of knowledge (genetic information) which boosts productivity in research and development (cf. pharmaceutical research or the search for new resistant crop varieties). Capital  $K$  includes not only physical capital but also human capital, and all other

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<sup>4</sup> (Double) subscripted function symbols refer to first (second) order partial derivatives. Dots over symbols denote time derivatives.

<sup>5</sup> The production function is non-decreasing in all arguments, i.e.  $Y_K > 0$ ,  $Y_{h_1} \geq 0$ ,  $Y_{h_2} \geq 0$ ,  $Y_N \geq 0$ ,  $Y_P > 0$ , and all inputs are essential, i.e.  $Y(\cdot) = 0$  if  $K \cdot h_1 \cdot h_2 \cdot N \cdot P = 0$ .



man-made capital that is not directly related to natural resource efficiency. Two kinds of technical knowledge are distinguished. First,  $h_1$  is the knowledge stock that can be accumulated endogenously. By spending a fraction of income on research and development activities, new techniques are developed. The development cost of this knowledge in terms of the final good is  $q$ . The second type of knowledge,  $h_2$ , is the result of exogenous technological progress, which occurs at rate  $\bar{g}$ :

$$\dot{h}_2/h_2 = \bar{g} \quad (3)$$

Society's preferences are modeled by the following intertemporal utility function:

$$W = \int_0^{\infty} U(c, N) \exp(-\vartheta t) dt \quad U_c > 0, U_{cc} < 0, U_N \geq 0. \quad (4)$$

where  $\vartheta$  is the rate of time preference or utility discount rate. Produced per capita consumption ( $c=C/L$ ) and environmental amenities (measured by  $N$ ) contribute to utility. The latter allows to take into account the existence value of the environment.

Optimal environmental policy follows from maximization of intertemporal utility (4) with respect to  $C$ ,  $P$ ,  $K$ , and  $h_1$ , subject the ecological constraint (1) and goods market constraint (2). This yields the following optimality conditions:

$$\frac{\dot{c}}{c} = \left( \frac{-U_c}{U_{cc}c} \right) \left[ r - \vartheta + \left( \frac{U_{cN}N}{U_c} \right) \frac{\dot{N}}{N} \right] \quad (5)$$

$$r = \frac{LU_N/U_c + Y_N}{Y_P} + E_N + \frac{\dot{Y}_P}{Y_P} = Y_K = \frac{Y_{h_1}}{q} \quad (6)$$

where  $L$  denotes population size.

Equation (5) represents the optimal savings rule and will be called the (modified) *Ramsey rule*. It expresses that consumers are willing to postpone consumption (i.e. allow a rise in consumption over time) the more the rate of return to postponing consumption exceeds the pure rate of time preference ( $\vartheta$ ). Whether the rate of return to postponing consumption is high not only depends on the reward to saving ( $r$ ), but also on future changes in the marginal



value of consumption because of improvements in environmental amenities (see the term with  $U_{cN}$  on the RHS of 5).

Equation (6) represents the optimal investment rule. Optimality requires that the marginal return to all kinds of capital are equalized. Hence, capital  $K$ , knowledge  $h$ , and environmental quality  $N$  should earn the same rate of return  $r$ . The return to capital and knowledge are their marginal product multiplied by their relative price. The return to environmental capital consists of four terms: its contribution to utility (the marginal amenity value), its contribution to total factor productivity, its contribution to ecological processes (marginal absorption capacity) and a capital gain because of future increases in the productivity of harvested natural resources. The first equality in (6) can be interpreted as the (generalized) *Hotelling rule*. To see this, note that the marginal product of pollution ( $Y_p$ ) is the price that producers in a decentralized economy are willing to pay for the extractive use of natural capital. The Hotelling rule states that (in the absence of extraction costs) the rate of increase in this price should equal the rate of return if the natural resource is exhaustible. The Hotelling rule for this model has to be modified to be applicable to renewable resources (so that  $E_N$  enters the equation) and to include productivity and amenity effects of  $N$ .

We further specify the production and utility function in such a way that the optimal growth path is characterized in the long run by sustainable growth path in which environmental quality remains constant and economic variables grow at a common rate  $g$ . First, the utility function is specified as:

$$U(c, N) = \frac{(c \cdot N^\phi)^{1-1/\sigma_c}}{1-1/\sigma_c}, \quad (7)$$

which implies that the elasticity of marginal utility is constant ( $U_{cc}c/U_c = -1/\sigma_c$ ) and that the share of amenities in utility is constant ( $U_N N/U_c = \phi$ ). The parameters  $\sigma$  and  $\phi$  should be interpreted as the elasticity of intertemporal substitution and the environmental preference parameter respectively. Since environmental quality is a public good and agents do not take into account the effects of their decision on its supply,  $\phi$  also measures the "consumption externality" associated with the environment.

Second, production technology is further specified as:

$$Y(\cdot) = A(N) \cdot F(Z, K) \quad A_N \geq 0, F_K > 0, F_Z > 0. \quad (8a)$$

$$Z = h \cdot P \quad (8b)$$

$$h = H(h_1, h_2) \quad H_{h1} > 0, H_{h2} > 0. \quad (8c)$$



where  $F(\cdot)$  and  $H(\cdot)$  are constant returns to scale functions,  $A$  should be interpreted as total factor productivity which depends on the quality of the environment,  $Z$  is polluting inputs measured in efficiency terms, and  $h$  is "resource-augmenting" technical knowledge which is a composite good of the two types of knowledge  $h_1$  and  $h_2$ . We assume that elasticities of substitution between  $K$  and  $Z$  and between  $h_1$  and  $h_2$  are not exceeding unity.<sup>6</sup>

Finally, population growth is assumed to be zero and population size is normalized to 1 so that  $C \equiv cL = c$ .

### 3. Steady state solution of the model

In the steady state, all environmental variables (environmental quality and pollution) are constant and all economic variables (output, consumption, investment, capital stock, and the knowledge stock) grow at a common growth rate  $g$ :

$$N = P = 0 \quad (9)$$

$$K/K = h/h = h_1/h_1 = Y/Y = \dot{c}/c = g \quad (10)$$

The common growth rate  $g$  will be equal to the rate of exogenous technological progress  $\bar{g}$ . The reason for the exogeneity of growth in the long run is the same as in the standard Solow growth model without environment. Diminishing returns with respect to man-made inputs imply that the returns to investment fall as long as the growth rate of man-made capital stocks ( $K$  and  $h_1$ ) exceeds the growth rate of basic technical knowledge. Hence, in order to maintain growth rates above the natural growth rate  $\bar{g}$ , it would be necessary to devote an increasing fraction of output to investment thereby reducing the consumption share finally to zero which is clearly suboptimal. The presence of environmental capital in the model does not change this basic mechanism of diminishing returns, since also the accumulation of environmental capital is subject to diminishing returns. This is due to the fact that the marginal absorption capacity falls with increases in environmental quality ( $E_{NN} < 0$ ), so that environmental improvement by means of pollution reduction becomes increasingly difficult. Intuitively, the richer the ecosystem or the cleaner the environment is, the more difficult it becomes to improve the environment even further.

However, the nature of the steady state changes dramatically if there are constant returns to scale with respect to all man-made factors of production. This is the case if the entire knowledge stock  $h$  is endogenously accumulated, i.e. if the contribution of basic

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<sup>6</sup> In the tables, these elasticities are denoted by  $\sigma_{KZ}$  and  $\sigma_H$  respectively.



knowledge ( $h_2$ ) is negligible.<sup>7</sup> In that case, the returns to investment in man-made capital do not fall and higher rates of growth can be reached by increasing the level of the investment rates without the need for continuously increasing investment rates. The parameter that represents the relative contribution of endogenous technological progress will therefore be used to distinguish between exogenous and endogenous growth.

Let us further characterize the steady state. Since  $K$ ,  $h$ , and  $h_1$  grow at the same rate, the production elasticities will be constant. It is useful to define the following elasticities:

$$a \equiv A_N N/A, \omega \equiv F_Z Z/F, \gamma \equiv H_{h_1} h_1/H, \quad (11)$$

where  $a$  is the production elasticity of nonrival environmental services,  $\omega$  is the production elasticity of effective pollution  $Z$  (and hence also of knowledge  $h$  and of pollution  $P$ ) and  $\gamma$  is the elasticity of the total knowledge stock  $h$  with respect to endogenously accumulated knowledge  $h_1$ . Due to the constant returns to scale assumptions, the production elasticity of capital is given by  $1-\omega$ , and the share of exogenous knowledge  $h_2$  in the total knowledge stock is  $1-\gamma$ .

Furthermore, it is useful to define aggregate man-made capital as:

$$M \equiv K + q \cdot h_1 \quad (12)$$

From the equality of the rates of return to capital (6), (11) and (12), we find:

$$r = (1-\omega)Y/K = \omega\gamma Y/(qh_1) = (1-\omega+\omega\gamma)Y/M \quad (13)$$

As is clear from (8) and (11),  $\omega$ ,  $\gamma$ ,  $Y/K$  and  $Y/h_1$  depend on  $N$ ,  $P$ ,  $h_1/h_2$ , and  $K/h_2$ . The second equality in (13) can be used to eliminate  $h_1/h_2$ . Furthermore, using (13) we can eliminate  $K/h_2$  by introducing  $M/h_2$ . The first equality in (13) then gives an expression for the rate of return to both man-made capital stocks, to be denoted by  $r^M$ :

$$r = r^M \equiv \begin{cases} f(N, P, M/h_2) & \text{if } \gamma < 1 \\ \rho(N, P) & \text{if } \gamma = 1 \end{cases}$$

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<sup>7</sup> There are other ways to get endogenous growth. If the elasticity of substitution between  $h_1$  and  $h_2$  is large enough (at least larger than 1 and sufficiently large relative to the share of knowledge in production), it is feasible to maintain a higher marginal product of man-made capital even if man-made capital stocks grow at a faster rate than  $h_2$  does. See Jones and Manuelli (1990) for the role of substitution in endogenous growth models.



where  $\partial r^M/\partial N > 0$ ,  $\partial r^M/\partial P > 0$ ,  $\partial r^M/\partial (M/h_2) \leq 0$ .

If  $\gamma < 1$ , exogenous technology is essential in production and there are diminishing returns with respect to reproducible capital. Hence, an increase in man-made capital relative to exogenous technology (i.e. an increase in  $M/h_2$ ) will lower the rate of return to man-made capital ( $r^M$ ). If  $\gamma = 1$ , there are constant returns to  $M$  and the rate of return to man-made capital only depends on pollution and environmental quality.

From the goods market equilibrium (2) and (11) we find  $C/Y = 1 - gM/Y$ . Combination of this result and (13) solves for the share of consumption in income:

$$C/Y = 1 - (1 - \omega + \omega\gamma) \cdot g/r \quad (15)$$

The Ramsey rule (5) establishes the relation between growth and interest rate in the long run. It expresses the long-run required rate of return on investment that maximizes utility, to be denoted by  $r^\mu$ :

$$r = \delta + g/\sigma_c \equiv r^\mu \quad (16)$$

To solve for the long-run optimal level of pollution and environmental quality, substitute the steady state conditions and definitions into (1) and the Hotelling rule (6):

$$P = E(N) \quad (17)$$

$$r = g + E_N(N) + (P/N) \cdot (a + \phi C/Y)/\omega. \quad (18)$$

We label expression at the RHS the steady state rate of return on environmental capital,  $r^N$ . Substitution of (15), (16) and (17) into (18) solves  $r^N$  in terms of  $N$ :

$$r = g + E_N(N) + \frac{E(N)/N}{\omega} \left[ a + \phi \left( 1 - \frac{(1 - \omega + \omega\gamma)g}{\delta + g/\sigma} \right) \right] \equiv r^N \quad (19)$$

Equations (14), (16), (17) and (19) will be used to characterize the steady state. For  $\gamma < 1$ , that is the case of exogenous growth, these three equations solve for  $r$ ,  $N$ , and  $M/h_2$ .<sup>8</sup> For

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<sup>8</sup> Also  $\omega$  and  $\gamma$  are endogenous variables unless the elasticities of substitution between  $K$  and  $Z$  and between  $h_1$  and  $h_2$  are unity. It is clear that  $\omega$  and  $\gamma$  can be written as functions of  $K/h_1$ ,  $h_1/h_2$  and  $P$  by manipulation of the production functions  $F(\cdot)$  and  $H(\cdot)$ . The condition  $Y_K = Y_{h_1}/q = r$  can be used to rewrite the ratios  $K/h_1$  and  $h_1/h_2$  in



the case of endogenous growth,  $M/h_2$  becomes irrelevant but the growth rate  $g$  becomes an endogenous variable.

Figure 1a is the graphical presentation of the steady state solution of the exogenous growth model. In the upper panel, the required rate of return  $r^u$  from equation (16) is confronted with the return to investment in the environment  $r^N$  from equation (19). Note that  $r^u$  is fixed in the long-run by preferences and the long-run growth rate. The point of intersection determines the optimal steady state level of environmental quality. Changes in the ratio of man-made capital relative to exogenous technology capital ( $M/h_2$ ) ensure that the rate of return to investment in the economy  $r^M$  equals the required rate  $r^u$ , see (14). The optimal pollution is easily found from (17) which is depicted in the middle panel. For completeness also the exogenously given long-run growth rate is depicted.

Figure 1b solves the endogenous growth model. In the upper panel, optimal environmental quality is determined by the point of intersection in which the rate of return to man-made capital  $r^M$  from equation (14) equals the rate of return to environmental capital  $r^N$  from equation (19).<sup>9</sup> Note that  $r^M$  increases for low values of  $N$  because, first, the absorption capacity improves, which allows for larger long-run levels of pollution [see (1), (17) and (19b)] and, second, total factor productivity improves [ $A_N > 0$ , see (8a)]. For high values of  $N$ ,  $r^M$  declines because decreases in the absorption capacity (and sustainable levels of pollution) dominate improvements in total factor productivity. The optimal level of pollution is determined in the middle panel and the associated growth rate in the lower panel. Growth depends on the intertemporal preference parameters but also on environmental quality and therefore on all the productivity parameters behind the  $\rho(\cdot)$  function, the ecological parameters behind the function  $E(\cdot)$ , and the environmental preference parameter  $\phi$ . For example, a decline in preference parameter  $\phi$  shifts the  $r^N$  curve downwards, see (19). Growth may increase if the  $r^N$  curve intersected  $r^M$  curve at its downward sloping part, but would fall if  $\phi$  was initially already so low that the upward sloping part of the  $r^M$  curve was relevant.

<REM> insert figure 1a and 1b <REM>

In Smulders (1995b) I have studied the consequences of changes in various parameters on the endogenous growth rate and environmental quality. Not only the long run (steady state) was examined but also transition dynamics. The main result is that there is an ambiguous

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terms of  $r$  and  $P$ . Equation (17) can be used to eliminate  $P$  and introduce  $N$  so that one finally finds  $\omega$  and  $\gamma$  in terms of  $N$ . In the sequel I will change the value of  $\gamma$  as if it were an exogenous variable. In fact, whenever  $\gamma$  is changed exogenously, this should be interpreted as a change in the "deeper" parameters of the CES production functions that determine  $\gamma$ .

<sup>9</sup> Since growth is endogenous now,  $g$  has to be eliminated from (19). From (14), (16), and (17) we find the expression for  $g$  that has to be substituted:  $g = [\rho(1, N, E(N)) - \delta] / \sigma_c$ .



relation between environmental quality and long-run growth. If existence and amenity values of the environment are low (low  $\phi$ ) and a clean environment boost workers' health productivity a lot ( $a$  high), an increase in environmental quality may increase the long-run growth rate. In Figure 1b this means that the  $r^N$  curve intersects the  $\beta'$  curve at its upward-sloping part.

Here the focus is on the role of technological change. In the next sections, the exogenous growth model ( $\gamma < 1$ ) is considered for different values of  $\gamma$ . Also the "limit case" with  $\gamma = 1$  is studied which allows a comparison between endogenous growth models and exogenous growth models. We first consider the steady state (section 4 and 5) before we turn to the dynamics (section 6 and 7).

#### 4. The long-run consequences of endogenous technological change ( $\gamma < 1$ )

Does optimal environmental policy in a world that relies mainly on exogenous technological progress differ much from optimal environmental policy in a world in which endogenous technological change plays a large role? Let us consider what happens in the model if the relative contribution of endogenous technological change, as captured by  $\gamma$ , increases.

Let us compare two economies, say A and B, that are different only with respect to the degree of endogeneity of technological change. In particular, it is assumed that both economies are in a steady state characterized by the same values for  $g$ ,  $r$ ,  $N$ ,  $P$ ,  $Y$ ,  $\omega$ ,  $a$ ,  $\phi$ . For simplicity, assume that the production functions in (2) and (8) are of the Cobb-Douglas type so that  $\omega$  and  $\gamma$  are parameters.<sup>10</sup> Economy A has no endogenous technological change ( $\gamma = 0$ ) while in economy B, technological progress is partly endogenous ( $0 < \gamma < 1$ ). With all other parameters equal, it follows immediately from eq. (15) and (18) that the consumption share  $C/Y$  and the return to investment in the environment  $r^N$  are lower in B than in A for any given environmental quality  $N$ . Figure 2 shows that the optimal level of environmental quality (for which  $r^N = r^u$ ) is lower in the economy with endogenous technological change. Constructing a similar example, it is straightforward to show that the larger the role of endogenous technological progress ( $\gamma$ ) is, the lower optimal environmental quality is in the social optimum. Hence, exogenous growth models based on exogenous technological change overestimate optimal environmental policy measures in the long run if in reality technological progress is at least partially endogenous.

<REM> insert Figure 2 <REM>

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<sup>10</sup> This assumption is not necessary for any of the arguments made. See next footnote.



The analysis so far deviates from policy issues in reality in an important respect. We normally think of environmental policy as the introduction of measures that serve to internalize externalities. The issue is how much pollution should be reduced or how much environmental quality should be improved. To put such a situation in the context of the model, we may assume that environmental quality is initially at a suboptimally low level like at  $N_0$  in Figure 2. It is clear that economy B with endogenous technological progress should improve its environment less than economy A.

The initial situation  $N_0$  may be the result of ignoring amenity values, i.e. the authorities responsible for environmental regulation have (incorrectly) set  $\phi$  equal to zero in their calculations. An environmental policy shock can thus be modelled by an increase in  $\phi$ , representing the situation that policy makers more fully take into account consumption externalities. An increase in  $\phi$  will increase the optimal long-run value for  $N$ , but the increase is smaller for a given increase in  $\phi$ , the larger  $\gamma$  initially is.<sup>11</sup>

In sum, a larger role for endogenous technological change implies that there is less room for improvement in long-run environmental quality in the optimum. With a larger role for endogenous technology development, total investment in the economy imposes a higher burden because a larger part of total knowledge has to be acquired by investment. Hence, there is less room for consumption ( $C/Y$  is smaller, see (15)) and it pays less to invest in amenities. Investment is more costly, which crowds out consumption of both material goods ( $C$ ) and of environmental amenities ( $N$ ). We will label this the "burden of investment effect". In contrast, in economies where most new techniques fall like manna from heaven, a larger part of production can be spent on consumption and the demand for a cleaner environment is accordingly higher.

## 5. The long-run consequences of endogenous growth ( $\gamma=1$ )

Does optimal environmental policy in a world of endogenous growth differ much from optimal environmental policy in a world in which the long-run growth rate is exogenously given? It will be shown in this section that this is indeed the case in the long run.

Consider the steady state impact on endogenous growth of the introduction of optimal environmental policy as modeled by an increase in  $\phi$ . In Figure 1b, which is the relevant steady state diagram for the endogenous growth model, the  $r^N$  curve shifts upward and the level of

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<sup>11</sup> With elasticities of substitution below unity,  $\gamma$  should be considered as a function of  $N$ . By changing the parameters of the CES specification (but keeping substitution elasticities the same), we calibrate an economy in which  $\gamma$  is higher for any level of  $N$  than in the benchmark economy with less endogenous technology. Hence, all arguments that are made in the text for the Cobb-Douglas specification carry over to the general case of CES functions.



environmental quality is higher in the new steady state than in the old one. The difference with the exogenous growth case is that now also the long-run rate of return changes. Changes in environmental quality have a permanent impact on the productivity of man-made assets as they are not offset by adjustments in the ratio of man-made capital to exogenous knowledge stocks. The change in the interest rate has an impact on the optimal level of long-run environmental quality that was not present in the exogenous growth model.

Figure 3 points out the implications of the change in the long-run rate of return. The starting situation, with suboptimally low environmental quality  $N_0$ , is represented by point S. Optimal environmental quality is found by equating the rate of return on environmental capital  $r^N$  to the rate of return on man-made assets  $r^M$ . If  $r$  remained unaffected, like in the exogenous growth model (in which it requires the required rate  $r''$  which is unaffected), point X would represent the optimum. In the endogenous growth case, however, the rate of return changes and point D represents the optimum.

Since  $r$  may fall or increase, depending on the shape of the  $r^M$  curve and the initial value of  $N$  (see the discussion of eq. (14) in section 3 above), we distinguish between two cases. If the interest rate falls in the long run, optimal environmental quality is higher in the endogenous growth case than in the case of a given long-run rate of return, while the opposite holds for an increasing long-run interest rate.

<REM> insert Figure 3 <REM>

Here we see a second important channel by which endogenous technological change makes tight environmental policy less desirable. In a world of endogenous growth, environmental policy has permanent effects on the productivity of the economy. If the rate of return to man-made capital increases, investment in a clean environment becomes less attractive relative to investment in economic growth. Note that this interest rate induced effect occurs in addition to the "burden of investment effect" that was present in the neoclassical steady state. Similarly, if the rate of return falls (because lower levels of polluting inputs reduce the productivity of man-made capital), optimal pollution abatement may be higher in a world of endogenous growth than in a world with substantial exogenous technological change. Then, the burden-of-investment effect is compensated by a shift in the *direction* of investment (away from investment in production towards abatement) that is induced by the decline in the productivity of man-made capital.

## 6. The short-run and medium-term consequences of endogenous technological change

In this section, it will be claimed that environmental policy should be more ambitious in the



short run if technological change is endogenous. A simple argument, that is very similar to the one in the previous section, provides the intuition behind this claim. Next we present numerical simulations of the transitional dynamics of the model to illustrate the impact of endogenous technological change on optimal policy over time.

#### *An heuristic argument*

To gain insight into the impact of endogenous technology on short-run optimal environmental policy, consider equation (14), depicted by the curve labeled  $r^M$  in figure 4. A given reduction in pollution reduces the return to investment in man-made capital ( $r^M$ ). The  $r^M$  curve shifts downward. Investment shifts from investment in the economy to investment in the environment. Man-made assets are accumulated at a slower pace now so that the ratio of man-made assets to exogenous technological knowledge  $M/h_2$  falls. More exogenous technological knowledge is available per unit of man-made capital which boosts rates of return. This is represented in the figure by a movement along the  $r^M$  curve to the left. As a result the rate of return to man-made assets recovers over time. Rising opportunity costs to environmental improvement induce reductions in environmental investment. Hence, on the optimal path, we expect low pollution levels initially when  $r^M$  is low, and thereafter gradual increases in pollution levels when rates of return recover.

How quickly  $r^M$  recovers depends on the extent of diminishing returns to capital and hence on  $\gamma$ . The larger  $\gamma$ , the slower is the recovery of rates of return, and the more persistently returns are below their steady state level ( $r^u$ ). The reason is that increases in exogenous knowledge boost the rate of return less the lower its importance in production (i.e. the larger  $\gamma$ ). The larger  $\gamma$ , the less diminishing returns with respect to reproducible capital play a role. The  $r^M$  curve in figure 4 is flatter the higher  $\gamma$ <sup>12</sup> is. Hence, with interest rates persistently lower because of endogenous technological change, incentives to invest in the economy are lower. Opportunity costs to investment in the environment are lower. Hence, it pays to invest more in the environment where rates of return are high. The direction of investment shifts to environmental investment. Note that this interest rate induced effect is the same one as was described for the long run in the endogenous growth case.

<REM> Insert Figure 4 <REM>

#### *Numerical simulations*

Numerical simulations of the full model give the same picture. Since four state variables characterize the model, the transition dynamics of the full model are too complex to study analytically. Therefore we linearize the model and use the simulation package developed by

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<sup>12</sup> Indeed in the limit case in which  $\gamma=1$ , the  $r^M$  curve is horizontal.



Markink and Van der Ploeg (1991) to generate numerical results.<sup>13 14</sup>

Our parameter choice (see footnote to Table 1) reflects a rough calibration of the model to some stylized facts. For example, we pick a growth rate of two percent, a share of capital  $(1-\omega)$  of one third, a rate of time preference of 3 percent, and an elasticity of intertemporal substitution of two third. There is less agreement about elasticities of substitution in production, apart from the fact that they probably are below one. The calibration of the ecological model block is chosen in such a way that the adjustment speed of the economy is in line with the literature on convergence. Not much is known about the production elasticity of environmental quality,  $a$ , on the very aggregate level. The reader should therefore keep in mind that the figures are merely an illustration of the possible order of magnitude of the effects and that the model simulations are intended to illustrate the qualitative directions of the results.

Let us first investigate the typical responses of economic and environmental variables over time, following the introduction of a tighter environmental policy stance. Table 1 and Figures 5 and 6 provide the numerical simulation results of a permanent increase in the preference parameter  $\phi$ , which is, as already explained, a way to model the introduction of a policy that more fully internalizes pollution externalities. All variables are calculated as percentage deviations from the initial steady state. The table displays results for three different parameterizations of technological change (three values for  $\gamma$ ) and two different levels of initial pollution ( $P/N$ ). First, attention will be paid to the common tendencies in the resulting six cases.

<REM> insert Table 1, Figures 5 and 6 <REM\>

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<sup>13</sup> The state variables are the two predetermined variables  $N$  and  $M$  and the instrument variables  $C$  and  $P$ . For all parameter combinations I tried, the linearized model generated two positive and two negative roots, so that the model turned out to be locally saddle-point stable. To give an impression of the speed of convergence, I report the negative roots ( $\lambda_1$  and  $\lambda_2$ ) for the numerical example in Table 2:

$\gamma$	$\lambda_1$	$\lambda_2$
$\gamma=0$	-0.1129	-0.0318
$\gamma=0.5$	-0.0686	-0.0183
$\gamma=0.99$	-0.0589	-0.0004
$\gamma=1$	-0.0587	0

<sup>14</sup> We are aware of the limitations of both linearization and numerical results. Linearization around the optimal steady state growth path seems not without problems when it is argued that the case of our interest (the real world situation) is an economy that is, first, far from its optimum, and, second, far from a steady state in ecological sense. However, by studying a shock to the preference parameter  $\phi$ , we start in a suboptimal steady state as is explained above. The second objection may also be less important here, since our aim is to find out how optimal policies change if endogenous technical change plays a larger role, rather than to find out how current policies should change in order to reach the optimum.



Initially the economy is on a balanced growth path with a suboptimally low level of environmental quality. At time zero, the optimal policy is introduced ( $\phi$  increases permanently), which will eventually raise the actual level of environmental quality to its optimal long-term level. The only way to improve the environment is a reduction in pollution. Polluting input levels fall at time zero which causes a reduction in the productivity of the economy. Output and the rate of return fall. Lower returns to man-made assets cause investment, as measured by the growth rate of man-made assets  $g_M$ , to fall. At the same time, the direction of investment shifts away from man-made assets to more investment in the environment. Consumption has to fall because of the drop in production, but falls less than investment since lower returns to savings imply a higher propensity to consume.

Over time, environmental quality improves. Investment shifts back from investment in environmental quality improvements to investment in man-made assets, as can be seen from decreasing emission reductions and higher growth rate of man-made capital  $g_M$ . This reversal of the direction of investment is the result of the increase in the return to investment in production relative to the return to pollution abatement which occurs for three reasons. First, a cleaner environment improves total factor productivity. Second, man-made capital becomes more scarcer in production because it grows at a lower rate as the rate of exogenous technological progress. Finally, pollution abatement becomes increasingly costly when the environment is already cleaner, due to the concavity of the absorption capacity  $E(N)$ .

#### *The effects on optimal environmental policy*

Now we return to the importance of endogenous technological change by comparing optimal policies for different values of the initial share of endogenously accumulated knowledge in production ( $\gamma$ ). The tables allow a comparison among an economy without endogenous technological progress ( $\gamma=0$ ), an economy with equal importance for exogenous and endogenous technological knowledge ( $\gamma=0.5$ ) and an economy that accumulates all knowledge endogenously (the endogenous growth case,  $\gamma=1$ ).<sup>15</sup>

If the contribution of endogenous technological change as measured by this share is larger, pollution has to be initially reduced more ( $P$  on time zero is smaller, see Tables 1 and 2). Environmental quality improves faster in early periods if the contribution of endogenous technological change is larger, showing that it is optimal to invest at a quicker pace in the environment rather than in the economy where rates of return are more persistently depressed.

Compared to the situation without endogenous technological change, pollution

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<sup>15</sup> Note that other important characteristics of the economy (notably the initial level of environmental quality and pollution, the initial growth rate and the initial share of pollution in production) are the same irrespective of  $\gamma$  (see footnote in Table 1). Such a sensitivity analysis is the relevant one for policy assessment, in which typically models have to be calibrated for a single given initial situation, but allowing for differences in the variable about which policy makers are uncertain (viz.  $\gamma$ ).



reduction on time  $t=0$  should be significantly higher. Table 2 points out that the situation with  $\gamma=0.5$  calls for 19 percent higher pollution reduction efforts, the one with  $\gamma=1$  calls for no less than 44 percent higher efforts.

#### *The effects on production and consumption*

The impact of endogenous technological progress on aggregate production and consumption levels depends on how environmental policy affects productivity in the long run. Recall that pollution reduction directly reduces output and productivity. However, since pollution reduction causes the environment to improve over time, and since total factor productivity depends on environmental quality, environmental policy might offset the initial adverse productivity effects after some period.<sup>16</sup>

In the left panel of Table 1, initial pollution is high relative to the stock of environmental capital. The environment improves quickly so that total factor productivity improvements compensate the adverse productivity effects of pollution reductions. The environment is mainly an investment good that enhances the productivity of the economy. Environmental policy acts (after a certain period) as a positive productivity shock. Rates of return are permanently higher in the endogenous growth case (so the situation depicted in Figure 3a is relevant). Also in the exogenous growth case, rates of returns increase but only temporarily. As a result, for all values of  $\gamma$  in the left panel of Table 1, investment is stimulated and long-run production and consumption are higher. The higher  $\gamma$ , the more persistent this positive productivity shock is and the more gains in production accumulate. Hence, production and consumption levels are higher for higher  $\gamma$ .

In the right panel of Table 1, in contrast, initial pollution is already low and further pollution reductions induce adverse productivity effect without being fully offset by total factor improvements. As a result, environmental policy acts as a negative productivity shock in not only the short run but also the long run. The more persistent this shock is (that is, the higher  $\gamma$  is), the larger the losses are in production and consumption.

## **7. Exogenous growth models versus endogenous growth models**

How are the two types of models related? In the case of exogenous growth ( $\gamma < 1$ ), rates of return and growth are affected only temporarily, whereas in the case of endogenous growth ( $\gamma = 1$ ), environmental policy has permanent effects on both variables. Interest rates are more

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<sup>16</sup> Improvements in environmental quality might improve the absorption capacity of the environment. This allows for higher sustainable levels of pollution which again boosts productivity in the long run. However, this only happens if  $E_N > 0$ , which was not assumed in the example.



persistently affected the larger  $\gamma$  is. When  $\gamma$  approaches one, the rate of convergence to the steady state of the exogenous growth model declines to zero. The steady state is reached only after an infinitely long period so that temporary effects in the exogenous growth model translate into permanent effects in the endogenous growth model.

If the role of endogenous technological change is large, the steady state of the exogenous growth model is not very informative about medium term effects. It takes a very long time to reach the steady state. In contrast, the steady state of the endogenous growth model "predicts" better the medium-term dynamics in a world with endogenous technological progress.

To illustrate, consider again the optimal environmental policy in an economy that starts from a suboptimally low level of environmental quality. In Section 4 it was shown that the steady state optimal level of environmental quality *decreases* if the value of  $\gamma$  is increased. However, in Section 5, it was shown that once  $\gamma$  takes its extreme value of 1, the long-run growth rate and interest rate become endogenous and optimal environmental quality *increases* (see Figure 3b). Hence, the steady state value of  $N$  as a function of  $\gamma$  shows a discontinuous jump at  $\gamma=1$  (cf. Figure 5). A comparison of the dynamics of the two types of growth models reveals however that the difference between them is less sharp than the comparison of steady states suggests. Table 2 gives results for the exogenous growth model with a value of  $\gamma$  very close to 1. The experiment is the same as in Section 6. Comparison of the results with those in the right panel of Table 1 reveals that over a very long time horizon the exogenous growth model with  $\gamma=0.99$  yields the same results as the endogenous growth model (with  $\gamma$  exactly equal to one). It takes a very long time before the exogenous growth model reaches its steady state. If the environment is mainly a consumption good ( $P/N$  low), environmental quality is higher than with lower  $\gamma$  over almost the entire horizon and the rate of return is lower (see right panel of Table 1 and lower panel Table 2). This clearly shows that the endogenous growth model is a good "predictor" of the medium and long run (but not the very long run or steady state) of the exogenous growth model if the role for endogenous technological change is large.

<REM> insert Table 2 <REM\>

## 8. Conclusions

If technological change is endogenous rather than exogenous, optimal environmental policy should be modified in three respects. The overall *burden* of investment, the optimal *direction* of investment and the optimal *timing* of investment are crucially dependent on how sensitive technological change is to research and development activities. Since environmental policy involves also investment (current pollution should be reduced and production foregone in



order to improve future environmental quality), these three investment effects affect the design of optimal environmental policy.

First, there is the *burden* of investment effect. If technological change is the result of costly research and development efforts, rather than a free good, the economy bears a larger burden of investment and a smaller fraction of income can be consumed. This implies that investment -- either investment in a clean environment or investment in productive capital and new technology -- pays less so that the optimal (steady state) level of environmental quality is lower.

Second, the *direction* of investment may be diverted from the environment towards production. If improvements in environmental quality improve the long-run productivity of the economy, investment in production becomes more attractive relative to investment in the environment, so that optimal environmental quality is lower. The higher the contribution of endogenous technology accumulation, the more sensitive the productivity of the economy is to changes in energy input levels and environmental quality, since the influence of an exogenous source of productivity improvements is lower. Environmental policy has two opposite effects on productivity. Pollution reduction reduces productivity but environmental quality improvements boost total factor productivity. If the former dominates the latter, environmental policy acts as a negative productivity shock, rates of return fall and investment shifts away from investment in production towards environmental investment. If, however, total factor productivity changes outweigh production losses because of pollution reduction, investment in the economy becomes relatively more attractive, thereby reducing relative efforts to clean up the environment.

Finally, endogenous technological change affects the *timing* of investment in a clean environment. A smaller role for exogenous technological change implies that emission reductions have a more persistent adverse effect on the productivity of the economy. Hence, with endogenous technical change, rates of return in production are low for a longer period which reduces the opportunity cost of investment in a clean environment. Hence, the existence of endogenous technological change provides the rationale to implement environmental policy at a quicker pace.

Not only the role of endogenous technological change is examined in this paper, but also exogenous growth models are contrasted to endogenous growth models. The latter arise as a limit case of the model with endogenous technological change if the returns to man-made factors of production are non-diminishing. The endogenous growth model allows for permanent effects of changes in environmental variables on the productivity of the economy. Whether this is a realistic property is an empirical issue. Currently, empirical research into this question is still lacking. Even if the case of endogenous growth turns out to be too extreme, it has its merits. The steady state picture that emerges from the endogenous growth model may be a better guide for environmental policy than the steady state picture from the exogenous



growth model. Exogenous growth models may be misleading if the steady state is give too much weight. The exogenous growth model rules out long-run changes in the interest rate and also the associated "direction of investment" effects.

This paper shows that the introduction of endogenous technological change has non-trivial implications for optimal environmental policy. The numerical calculation in this paper show that the impact of endogenous technological change on short-run pollution reduction policies may be large. If half of technological change is endogenously generated, first-period pollution reduction should be 16 to 19 percent higher than when technological progress is completely exogenous. With respect to long-run abatement policies, the figures involved turn out to be much smaller (if not negligible). However a more careful numerical calibration of the model is needed to assess the quantitative impacts, which is left for future research. It is clear that the entire time path of environmental policy should be taken into account in such a calibration. Moreover, it is no longer appropriate to examine only small changes in a linearized model. Another direction for future research is a decentralized model in which the private incentives to invest in clean technologies and abatement are explicitly modeled. Finally, the new types of growth models inspire new empirical research. There are many opportunities in which the combination of new growth theory and environmental issues, both in theoretical and empirical research, can contribute to our understanding of the best ways to enhance sustainable development.



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## Figures

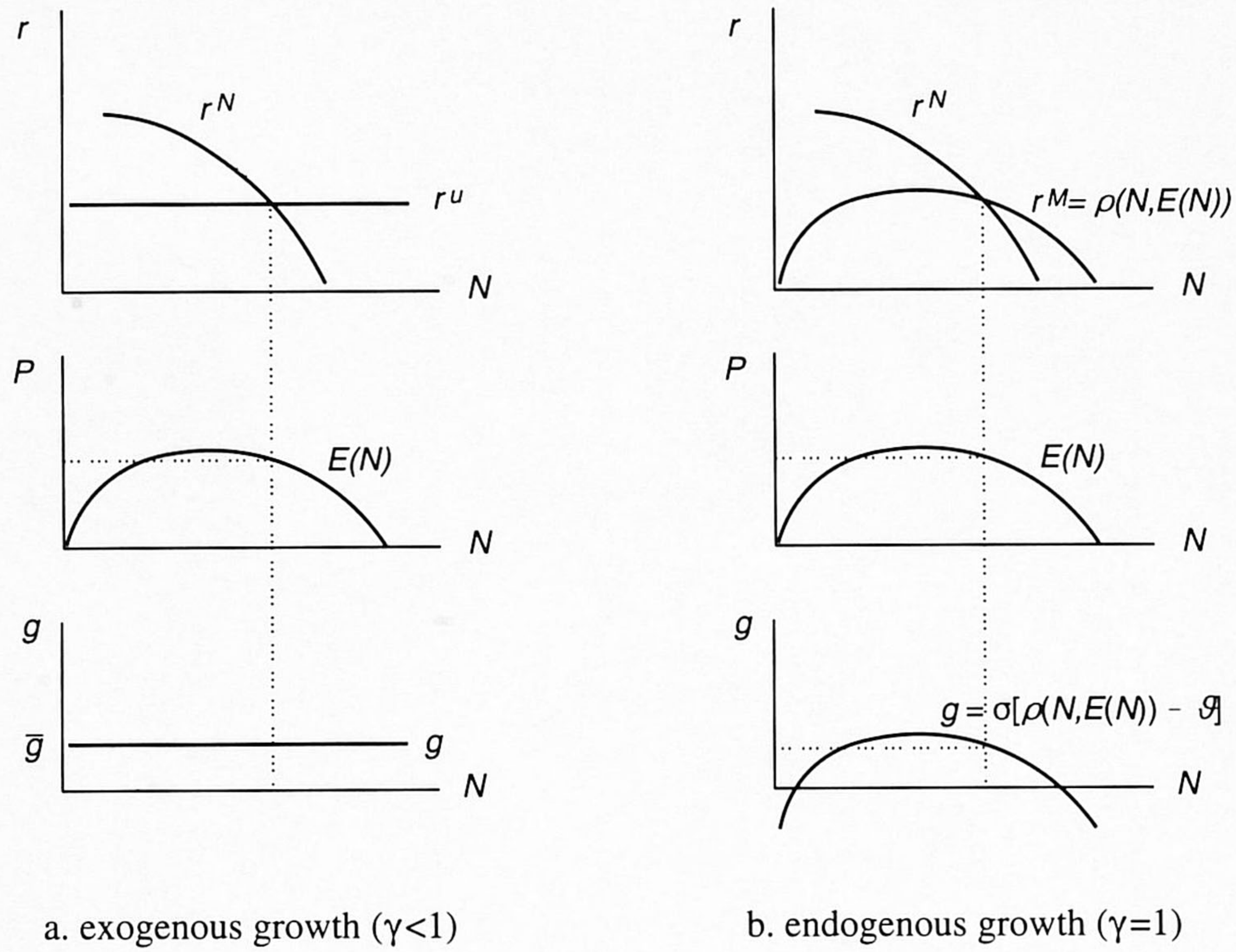


Figure 1: Steady state solution for the exogenous growth case and the endogenous growth case.

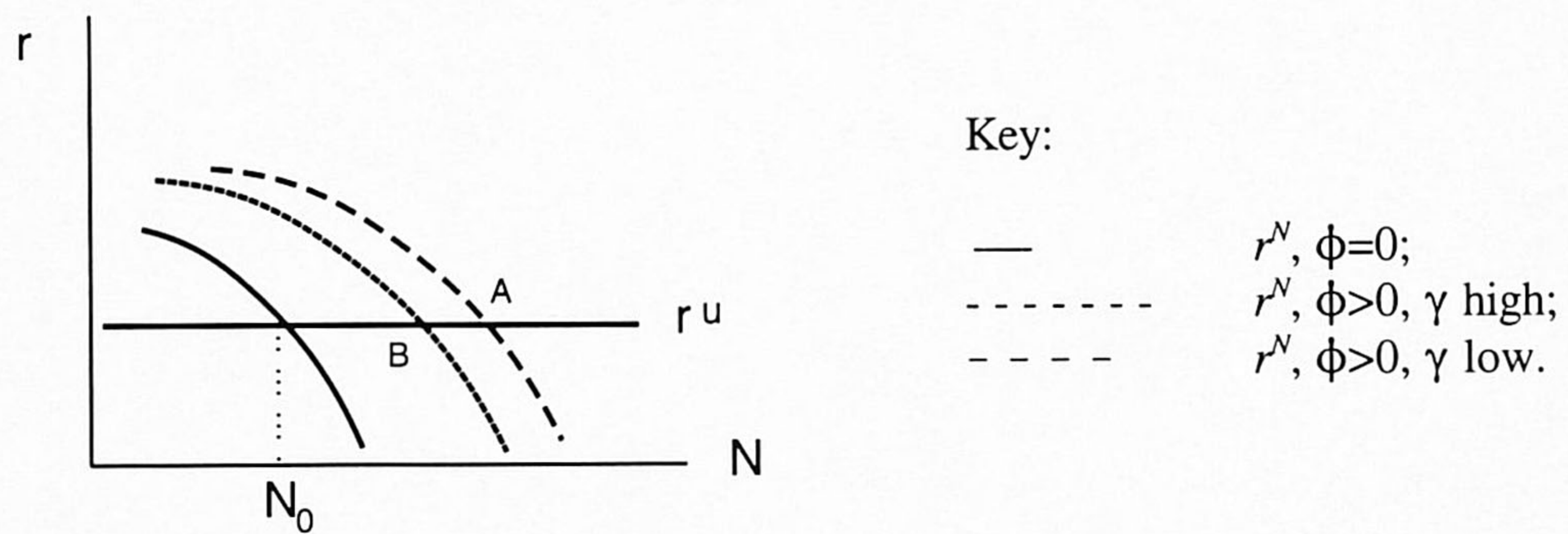


Figure 2: Optimal environmental policy (steady state) in the exogenous growth model



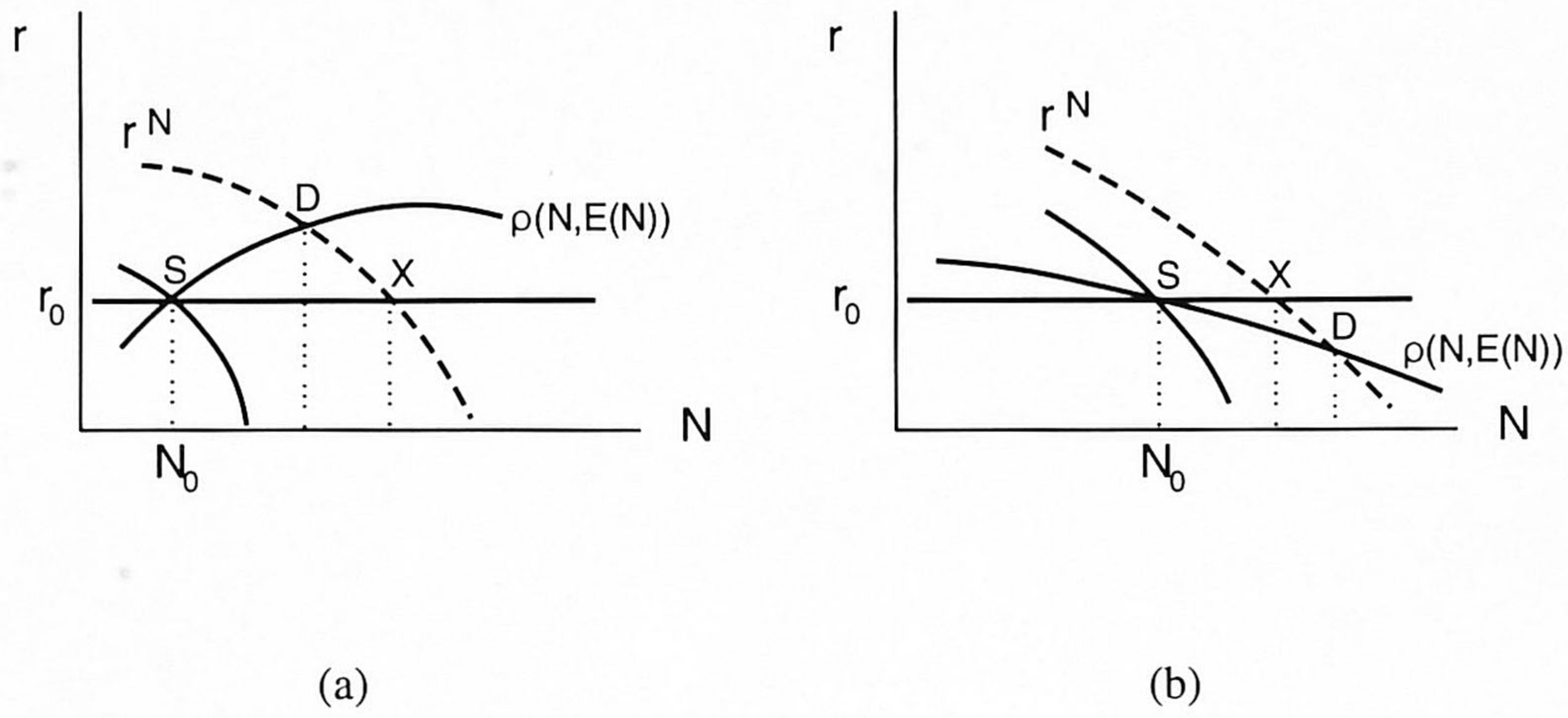


Figure 3: The impact of endogenous changes in the steady state interest rate and growth rate: (a) environment as an investment good; (b) environment as a consumption good.

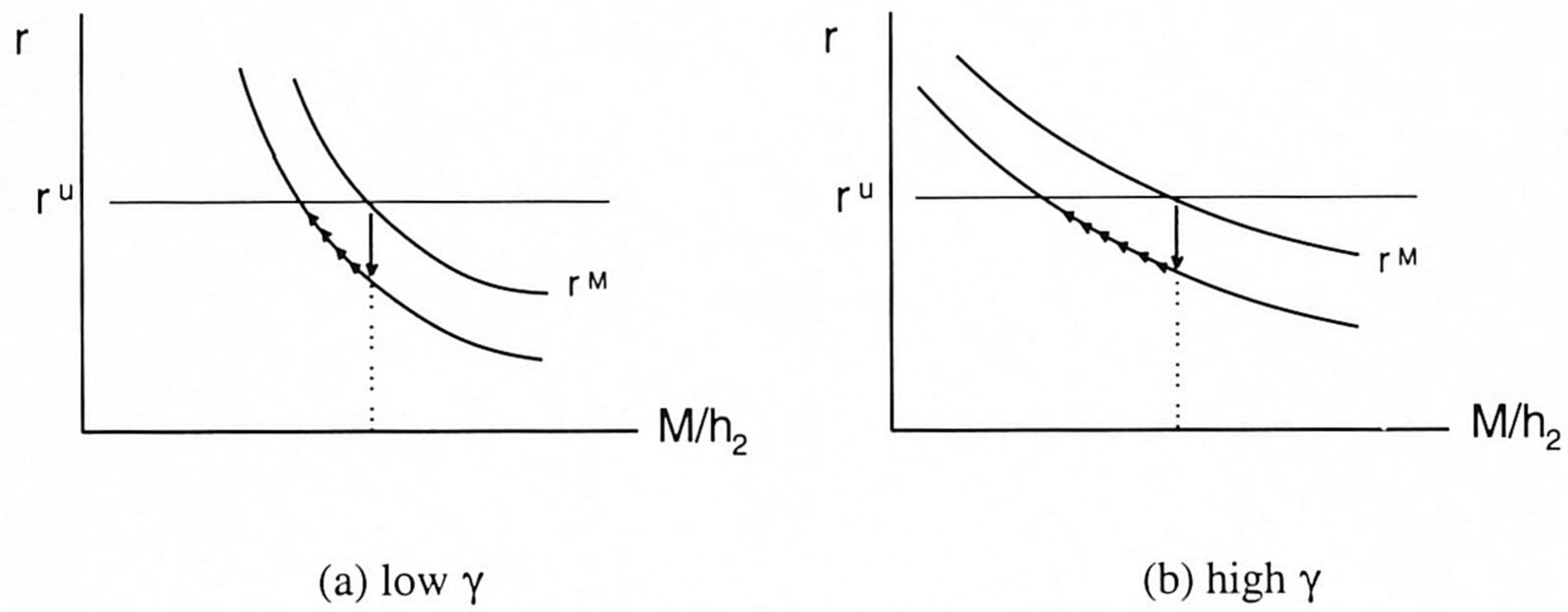


Figure 4: The impact of a permanent reduction in  $P$  on the rate of return to man-made assets  $r^M$  in the exogenous growth case ( $\gamma < 1$ ). (For simplicity, the figure ignores effects from  $P$  on  $A$  via  $N$ , i.e.  $a=0$  is assumed).



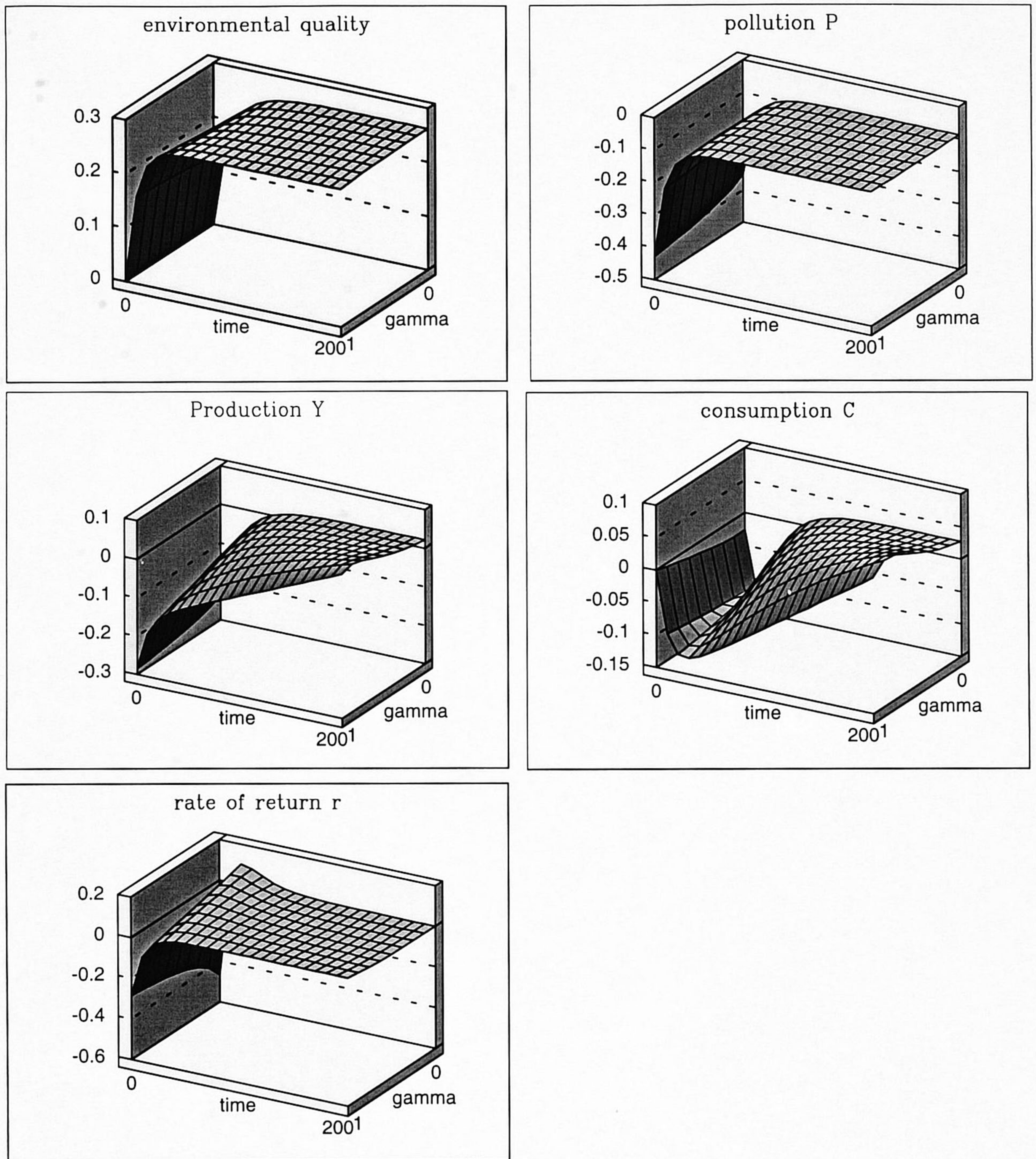


Figure 5: Simulation results; environment as an investment good (parameters reported in Table 1)



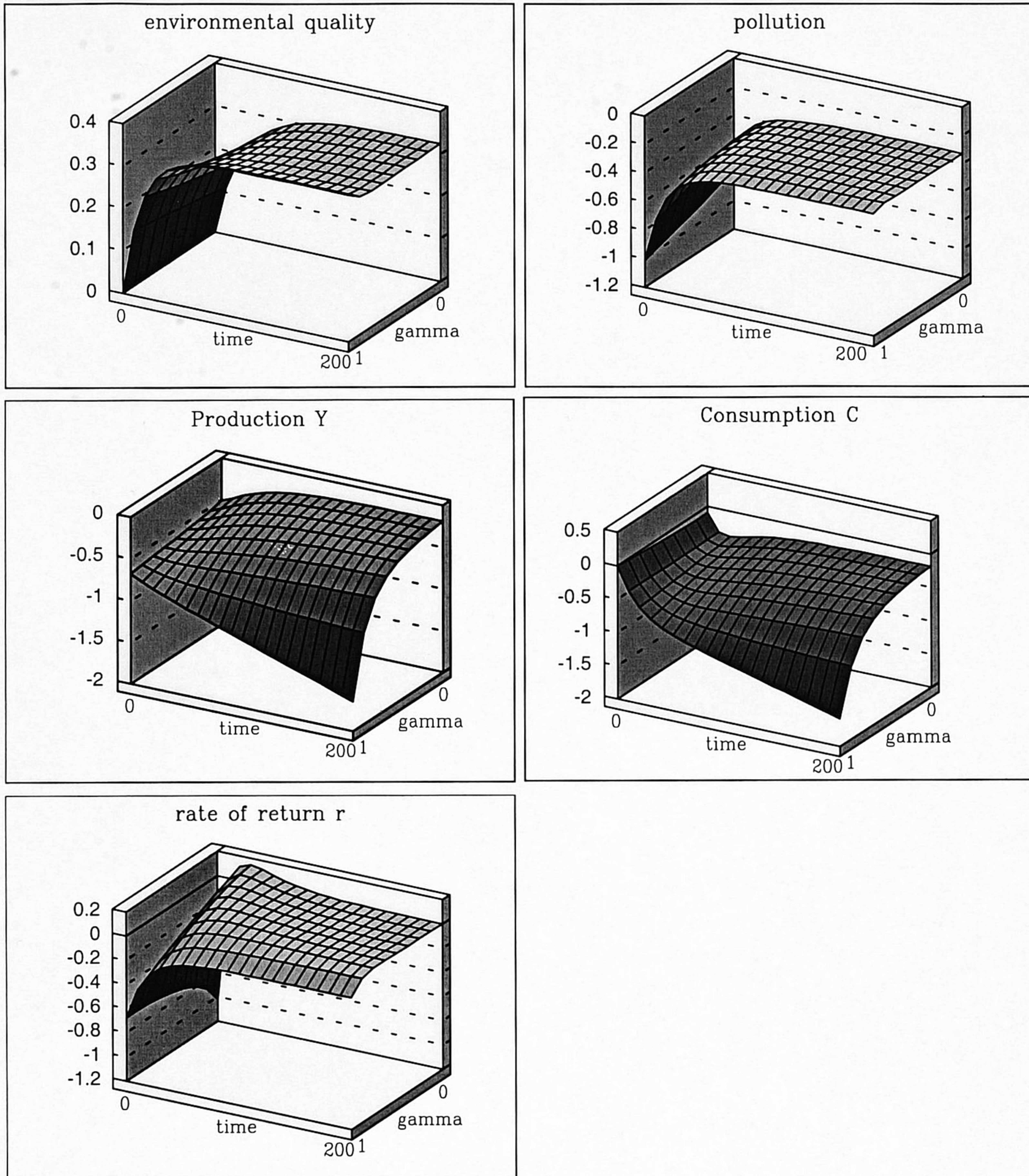


Figure 6: Simulation results; environment as a consumption good (parameters reported in Table 1)



Table 1 Optimal environmental policy<sup>a</sup> (percentage deviations from initial steady state).

		the environment as investment good ( $P/N=0.06$ )				the environment as consumption good ( $P/N=0.02$ )			
		$t=0$	$t=10$	$t=50$	$\infty$	$t=0$	$t=10$	$t=50$	$\infty$
$\gamma=0$	$N$	0	0.1374	0.2405	0.2623	0	0.1131	0.2708	0.3248
	$P$	-0.3513	-0.1883	-0.0991	-0.0874	-0.7633	-0.5296	-0.3575	-0.3248
	$r$	-0.4684	0.0190	0.0614	0	-1.0177	-0.1184	0.1009	0
	$g_M$	-1.8987	-0.1804	0.1423	0	-3.859	-0.8543	0.1816	0
	$C$	-0.0261	-0.1092	-0.0232	0.0273	-0.0901	-0.3511	-0.2807	-0.1827
	$Y$	-0.2342	-0.1358	-0.0143	0.0218	-0.5088	-0.4529	-0.2699	-0.1895
	$M$	0	-0.1682	-0.0851	-0.0219	0	-0.4125	-0.3655	-0.2436
$\gamma=0.5$	$N$	0	0.1535	0.2432	0.2621	0	0.1341	0.2829	0.3220
	$P$	-0.4061	-0.2003	-0.0923	-0.0874	-0.9080	-0.6150	-0.3386	-0.3220
	$r$	-0.3199	-0.0457	0.0586	0	-0.7154	-0.2762	0.0709	0
	$g_M$	-1.1550	-0.2610	0.1212	0	-2.4691	-1.0719	0.1122	0
	$C$	-0.0180	-0.1030	-0.0687	0.0593	-0.0728	-0.3563	-0.4879	-0.3104
	$Y$	-0.2707	-0.1661	-0.0495	0.0546	-0.6053	-0.5903	-0.4661	-0.3085
	$M$	0	-0.1256	-0.1036	0.0382	0	-0.3375	-0.5020	-0.3018
$\gamma=1$	$N$	0	0.1620	0.2513	0.2559	0	0.1532	0.3265	0.3448
	$P$	-0.4277	-0.2109	-0.0915	-0.0853	-1.0128	-0.716	-0.3802	-0.3448
	$r$	-0.2851	-0.0866	0.0228	0.0284	-0.6752	-0.4263	-0.1446	-0.1149
	$g_M$	-0.8554	-0.2778	0.0403	0.0569	-2.0255	-1.2278	-0.3251	-0.2299
	$C$	0	-0.0948	-0.1192	- <sup>b</sup>	0	-0.03431	-0.8633	- <sup>b</sup>
	$Y$	-0.2851	-0.1904	-0.1104	- <sup>b</sup>	-0.6752	-0.7439	-0.9535	- <sup>b</sup>
	$M$	0	-0.1038	-0.1332	- <sup>b</sup>	0	-0.3176	-0.8089	- <sup>b</sup>

<sup>a</sup> Simulation results of a 1 percent increase in  $\phi$ . Calculations based on the linearized model. Initial steady state:  $g=0.02$ ,  $\omega=2/3$ ,  $E_N=-0.02$ ,  $E_{NN}N=-0.03$ ,  $a=1/3$ ,  $A''N/A'=-2/3$ ,  $\sigma_{KZ}=0.5$ ,  $\sigma_H=0.75$ ,  $\sigma_c=2/3$ ,  $\theta=0.03$ . The initial value of  $\phi$  is set at a value such that the initial steady state is an optimum.

<sup>b</sup> Since the long-run growth rate of this variable changes, the deviation from the initial steady state becomes (minus) infinity in the long run.



Table 2 Optimal environmental policy if exogenous technological change is negligible<sup>a</sup>  
(percentage deviations from initial steady state).

		$t=0$	$t=10$	$t=50$	$t=100$	$t=200$	$t=400$	$\infty$
investment	$N$	0	0.1620	0.2541	0.2559	0.2561	0.2565	0.2619
good <sup>b</sup>	$P$	-0.4280	-0.2108	-0.0875	-0.0853	-0.0854	-0.0855	-0.0873
	$r$	-0.2860	-0.0859	0.0273	0.0288	0.0279	0.0260	0
	$g_M$	-0.8609	-0.2776	0.0527	0.0577	0.0558	0.0520	0
	$C$	-0.0004	-0.0951	-0.1083	-0.0513	0.0622	0.2776	3.2695
	$Y$	-0.2853	-0.1900	-0.0957	-0.0370	0.0759	0.2901	3.2658
	$M$	0	-0.1042	-0.1228	-0.0658	0.0478	0.2634	3.2584
consumpt.	$N$	0	0.1530	0.3253	0.3419	0.3420	0.3402	0.3184
good <sup>c</sup>	$P$	-1.0123	-0.7144	-0.3781	-0.3443	-0.3415	-0.3398	-0.3184
	$r$	-0.6763	-0.4235	-0.1371	-0.1068	-0.1012	-0.0937	0
	$g_M$	-2.0337	-1.2248	-0.3099	-0.2154	-0.2024	-0.1874	0
	$C$	-0.0022	-0.3443	-0.8536	-1.0991	-1.5131	-2.2912	-12.0330
	$Y$	-0.6748	-0.7412	-0.9386	-1.1520	-1.5618	-2.3353	-12.0200
	$M$	0	-0.3180	-0.8003	-1.0434	-1.4578	-2.2371	-11.9937

<sup>a</sup> Simulation results of a one percent increase in  $\phi$ . Calculations are based on the linearized model. Initial steady state:  $\gamma=0.99$ ;  $P/N$ , see below; other parameters, see Table 1.

<sup>b</sup>  $P/N = 0.06$  in initial steady state.

<sup>c</sup>  $P/N = 0.02$  in initial steady state.